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Large Scale Air Shower Simulations and the Search for New Physics at AUGER

Alessandro Cafarella[1*], Claudio Corianò[1†] and Alon E. Faraggi[2‡]

[1] *Dipartimento di Fisica, Universita' di Lecce, I.N.F.N. Sezione di Lecce, Via Arnesano, 73100 Lecce, Italy*

[2] *Theoretical Physics Department, University of Oxford, Oxford, OX1 3NP, United Kingdom*

Abstract

Large scale airshower simulations around the GZK cutoff are performed. An extensive analysis of the behaviour of the various subcomponents of the cascade is presented. We focus our investigation both on the study of total and partial multiplicities along the entire atmosphere and on the geometrical structure of the various cascades, in particular on the lateral distributions. The possibility of detecting new physics in Ultra High Energy Cosmic Rays (UHECR) at AUGER is also investigated. We try to disentangle effects due to standard statistical fluctuations in the first proton impact in the shower formation from the underlying interaction and comment on these points. We argue that theoretical models predicting large missing energy may have a chance to be identified, once the calibration errors in the energy measurements are resolved by the experimental collaborations, in measurements of inclusive multiplicities.

*Alessandro.Cafarella@le.infn.it
†Claudio.Coriano@le.infn.it
‡faraggi@thphys.ox.ac.uk

1 Introduction

One of the most intriguing experimental observations of recent years is the detection of Ultra–High–Energy–Cosmic–Rays (UHECR), with energy in excess of the Greisen–Zatsepin–Kuzmin (GZK) cutoff [1] (for a review see [2]). While its validity is still under some dispute, it is anticipated that the forthcoming AUGER [3] and EUSO [4] experiments will provide enough statistics to resolve the debate. From a theoretical perspective, the Standard Model of particle physics and its Grand Unified extensions indicate that many physical structures may lie far beyond the reach of terrestrial collider experiments. If this eventuality materializes it may well be that the only means of unlocking the secrets of the observed world will be mathematical rigor and peeks into the cosmos in its most extreme conditions. In this context the observation of UHECR is especially puzzling because of the difficulty in explaining the events without invoking some new physics. There are apparently no astrophysical sources in the local neighborhood that can account for the events. The shower profile of the highest energy events is consistent with identification of the primary particle as a hadron but not as a photon or a neutrino. The ultrahigh energy events observed in the air shower arrays have muonic composition indicative of hadrons. The problem, however, is that the propagation of hadrons over astrophysical distances is affected by the existence of the cosmic background radiation, resulting in the GZK cutoff on the maximum energy of cosmic ray nucleons $E_{\rm GZK} \leq 10^{20}$ eV [5]. Similarly, photons of such high energies have a mean free path of less than 10 Mpc due to scattering from the cosmic background radiation and radio photons. Thus, unless the primary is a neutrino, the sources must be nearby. On the other hand, the primary cannot be a neutrino because the neutrino interacts very weakly in the atmosphere. A neutrino primary would imply that the depths of first scattering would be uniformly distributed in column density, which is contrary to the observations.

The most exciting aspect of the UHECR is the fact that the AUGER and EUSO experiments will explore the physics associated with these events, and provide a wealth of observational data. Clearly, the first task of these experiments is to establish whether the GZK cutoff is violated, and to settle the controversy in regard to the air shower measurement.

2 Probing new physics with UHECR

We may, however, entertain the possibility that these experiments can probe various physics scenarios. In the first place, the center of mass energy in the collision of the primary with the atmosphere is of the order of 100 TeV and exceed the contemporary, and forthcoming, collider reach by two orders of magnitude. Thus, in principle the air shower analysis should be sensitive to any new physics that is assumed to exist between the electroweak scale and the collision scale due to the interaction of the primaries with the atmospheric nuclei. Other exciting possibilities include the various

explanations that have been put forward to explain the existence of UHECR events [6, 7, 8, 9, 10], and typically assume some form of new physics. One of the most intriguing possible solutions is that the UHECR primaries originate from the decay of long–lived super–heavy relics, with mass of the order of 10^{12-15} GeV [7, 8, 9, 10]. In this case the primaries for the observed UHECR would originate from decays in our galactic halo, and the GZK bound would not apply. This scenario is particularly interesting due to the possible connection with superstring theory. From the particle physics perspective the meta–stable super–heavy candidates should possess several properties. First, there should exist a stabilization mechanism which produces the super–heavy state with a lifetime of the order of $10^{17}s \leq \tau_X \leq 10^{28}s$, and still allows it to decay and account for the observed UHECR events. Second, the required mass scale of the meta–stable state should be of order, $M_X \sim 10^{12-13}$GeV. Finally, the abundance of the super–heavy relic should satisfy the relation $(\Omega_X/\Omega_0)(t_0/\tau_X) \sim 5\times10^{-11}$, to account for the observed flux of UHECR events. Here t_0 is the age of the universe, τ_X the lifetime of the meta–stable state, Ω_0 is the critical mass density and Ω_X is the relic mass density of the meta–stable state. It is evident that the parameters of the super–heavy meta–stable states are sufficiently flexible to accommodate the observed flux of UHECR, while evading other constraints [10].

Superstring theory inherently possesses the ingredients that naturally give rise to super–heavy meta–stable states. Such states arise in string theory due to the breaking of the non–Abelian gauge symmetries by Wilson lines. The massless spectrum then contains states with fractional electric charge or "fractional" $U(1)_{Z'}$ charge [11, 12, 13]. The lightest states are meta–stable due to a local gauge, or discrete, symmetry [13, 14]. This phenomenon is of primary importance for superstring phenomenology. The main consequence is that it generically results in super–massive states that are meta–stable. The super–heavy states can then decay via the non-renormalizable operators, which are produced from exchange of heavy string modes, with lifetime $\tau_x > 10^{7-17}$ years [12, 8, 10]. The typical mass scale of the exotic states will exceed the energy range accessible to future collider experiments by several orders of magnitude. The exotic states are rendered super–massive by unsuppressed mass terms [15], or are confined by a hidden sector gauge group [12]. String models may naturally produce mass scales of the required order, $M_X \approx 10^{12-13}$GeV, due to the existence of an hidden sector that typically contains non–Abelian $SU(n)$ or $SO(2n)$ group factors. The hidden sector dynamics are set by the initial conditions at the Planck scale, and by the hidden sector gauge and matter content, $M_X \sim \Lambda^{\alpha_s,M_S}_{\text{hidden}}(N,n_f)$. Finally, the fact that $M_X \sim 10^{12-13}$GeV implies that the super–heavy relic is not produced in thermal equilibrium and some other production mechanism is responsible for generating the abundance of super–heavy relic [13].

The forthcoming cosmic rays observatories can therefore provide fascinating experimental probes, both to the physics above the electroweak scale as well as to more exotic possibilities at a much higher scale. It is therefore imperative to develop the theoretical tools to decipher the data from these experiments. Moreover, improved

information on the colliding primaries may reveal important clues on the properties of the decaying meta–stable state, which further motivates the development of such techniques. In this paper we make a modest step in this direction, by studying possible modifications of air shower simulations, that incorporate the possible effects of new physics above the electroweak scale. This is done by varying the cross section in the air shower codes that are used by the experimentalists. In this respect we assume here for concreteness that the new physics above the electroweak scale remains perturbative and preserve unitarity, as in the case of supersymmetric extensions of the Standard Model. This in turn is motivated by the success of supersymmetric gauge coupling unification [16] and their natural incorporation in string theories. In the case of supersymmetry the deviations from the Standard Model are typically in the range of a few percent, a quantitative indication which we take as our reference point for study.

2.1 Possible Developments

Even if the forthcoming experiments will confirm the existence of UHECR events, it remains to be seen whether any new physics can be inferred from the results. We will argue that this is a very difficult question.

A possible way, in the top-down models of the UHECR interaction is to optimize the analysis of any new high energy primary interaction. One should keep in mind that the information carried by the primaries in these collisions is strongly "diluted" by their interaction with the atmosphere and that large statistical fluctuations are immediately generated both by the randomness of the first impact, the variability in the zenith angle of the impact, and the natural fluctuations in the - extremely large - phase space available at those energies. We are indeed dealing with *extreme* events. These uncertainties are clearly mirrored even in the existing Monte Carlo codes for the simulation of air showers, and, of course, in the real physical process that these complex Monte Carlo implementations try, at their best, to model (see also [17] for the discussion of simulation issues) . Part of our work will be concerned primarily with trying to assess, by going through extensive air-shower simulations using existing interaction models - at the GZK and comparable energies - the main features of the showers, such as the multiplicities at various heights and on the detector plane. We will illustrate the geometry of a typical experimental setup to clarify our method of analysis and investigate in detail some geometrical observables.

A second part of our analysis will be centered around the implications of a modified first impact on the multiplicities of the subcomponents. Our analysis here is just a first step in trying to see whether a modified first impact cross section has any implication on the multiplicity structure of the shower. The analysis is computationally very expensive and has been carried out using a rather simple strategy to render it possible. We critically comment on our results, and suggest some possible improvements for future studies.

3 Simulation of Airshowers

The quantification of the variability and parametric dependence of the first impact in the formation of extensive airshowers can be discussed, at the moment, only using Monte Carlo event generators. Although various attempts have been made in the previous literature to model the spectrum of a generic "X-particle" decay in various approximations, all of them include - at some level and with variants - some new physics in the generation of the original spectrum. In practice what is seen at experimental level is just a single event, initiated by a single hadron (a proton) colliding with an air nucleus (mostly of oxygen or nitrogen) within the 130 km depth of the Earth atmosphere. Our studies will show that the typical strength of the interaction of the primary at the beginning of the showers - at least using the existing Monte Carlo codes - has to increase fairly dramatically in order to be able to see - at the experimental level - any new physics.

Our objective here is to assess the actual possibility, if any, to detect new physics from the high energy impact of the primary cosmic ray assuming that other channels open up at those energies. Our investigation here is focused on the case of supersymmetry, which is the more widely accepted extension of the Standard Model. Other scenarios are left for future studies.

We recall that at the order of the GZK cutoff, the center of mass energy of the first collision reaches several hundreds of TeVs and is, therefore, above any supersymmetric scale, according to current MSSM models. It is therefore reasonable to ask weather supersymmetric interactions are going to have any impact on some of the observables that are going to be measured.

We will provide enough evidence that supersymmetric effects in total hadronic cross sections cannot raise the hadronic nucleon nucleon cross section above a (nominal) 100% upper limit. We will then show that up to such limit the fluctuations in 1) the multiplicity distributions of the most important components of the (ground) detected airshowers and 2) the geometric distributions of particles on the detector are overwhelmly affected by natural (statistical) fluctuations in the formation of the air showers and insignificantly by any interaction whose strength lays below such 100% nominal limit.

In order to proceed with our analysis we need to define a set of basic observables which can be used in the characterization of the shower at various heights in the atmosphere.

There are some basic features of the shower that are important in order to understand its structure and can be summarized in: 1) measurements of its multiplicities in the main components; 2) measurements of the geometry of the shower. Of course there are obvious limitations in the study of the development of the shower at the various levels, since the main observations are carried out on the ground. However, using both Cerenkov telescopes and fluorescence measurements by satellites one hopes to reconstruct the actual shape of the shower as it develops in the atmosphere.

To illustrate the procedure that we have implemented in order to characterize the shower, we have assumed that the first (random) impact of the incoming primary (proton) cosmic ray takes place at zero zenith angle, for simplicity. We have not carried out simulations at variable zenith, since our objective is to describe the main features of the shower in a rather simple, but realistic, setting. We have chosen a flat model for the atmosphere and variable first impacts, at energies mainly around the GZK cutoff region. Our analysis has been based on CORSIKA [18] and the hadronization model chosen has been QGSJET [19].

Measurements at any level are performed taking the arrival axis (z-axis) of the primary as center of the detector. The geometry of the shower on the ground and at the various selected observation levels has been always measured with respect to this axis. The "center" of the detector is, in our simulations, assumed to be the point at which the z-axis intersects the detector plane. Below, the word "center" refers to this particular geometrical setting.

The shower develops according to an obvious cylindrical symmetry around the vertical z-axis, near the center. The various components of the showers are characterized at any observation level by this cylindrical symmetry. Multiplicities are plotted after integration over the azimuthal angle and shown as a function of the distance from the core (center), in the sense specified above.

The showers show for each subcomponent specific locations of the maxima and widths of the associated distributions. We will plot the positions of the maxima along the entire spatial extent of the shower in the atmosphere. These plots are useful in order to have an idea of what is the geometry of the shower in the 130 km along which it develops.

4 Features of the Simulation

Most of our simulations are carried out at two main energies, 10^{19} and 10^{20} eV. Simulations have been performed on a small cluster running a communication protocol (openmoses) which distributes automatically the computational load. The simulation program follows each secondary from beginning to end and is extremely time and memory intensive. Therefore, in order to render our computation manageable we have implemented in CORSIKA the thinning option [20], which allows to select only a fraction of the entire shower and followed its development from start to end. We recall that CORSIKA is, currently, the main program used by the experimental collaborations for the analysis of cosmic rays. The results have been corrected statistically in order to reproduce the result of the actual (complete) shower. The CORSIKA output has been tokenized and then analyzed using various intermediate software written by us. The number of events generated, even with the thinning algorithm, is huge at the GZK energy and requires an appropriate handling of the final data. We have performed sets of run and binned the data using bins of 80 events,

where an event is a single impact with its given parametric dependence. The memory cost of a statistically significant set of simulations is approximately 700 GigaBytes, having selected in our simulations a maximal number of observations levels (9) along the entire height of the atmosphere.

4.1 Multiplicities on the Ground

We show in Fig. 1 results for the multiplicities of the photon component and of the $e^{\pm}$ components at 10^{19} eV plotted against the distance from the core (center) of the detector. For photons, the maximum of the shower is around 90 meters from the center, as measured on the plane of the detector. As evident from the plot, the statistics is lower as we get closer to the central axis (within the first 10 meters from the vertical axis), a feature which is typical of all these distributions, given the low multiplicities measured at small distances from the center. For electrons and positrons the maxima also lie within the first 100 meters, but slightly closer to the center and are down by a factor of 10 in multiplicities with respect to the photons. Positron distributions are suppressed compared to electron distributions. It is also easily noticed that the lower tail of the photon distribution is larger compared to the muon distribution, but all the distributions show overall similar widths, about 1 km wide.

Multiplicities for muons (see Fig. 2) are a factor 1000 down with respect to photons and 100 down with respect to electrons. The maxima of the muon distributions are also at comparable distance as for the photons, and both muon and antimuons show the same multiplicity.

At the GZK energy (Figs 3, 4) the characteristics of the distributions of the three main components (photons, electrons, muons) do not seem to vary appreciably, except for the values of the multiplicities, all increased by a factor of 10 respect to the previous plots. The maxima of the photons multiplicities are pushed away from the center, together with their tails. There appears also to be an increased separation in the size of the multiplicities of electrons and positrons and a slightly smaller width for the photon distribution compare to the lower energy result (10^{19} eV). We should mention that all these gross features of the showers can possibly be tested after a long run time of the experiment. Our distributions have been obtained averaging over sets of 80 events with independent first impacts.

5 Missing multiplicities?

Other inclusive observables which are worth studying are the total multiplicities, as measured at ground level, versus the total energy of the primary. We show in Fig. 5 a double logarithmic plot of the total multiplicities of the various components versus the primary energy in the range $10^{15} - 10^{20}$ eV, which appears to be strikingly linear.

From our result it appears that the multiplicities can be fitted by a relation of the form y=m*x+q, where $y = \mathrm{Log(N)}$ and $x = \mathrm{Log(E)}$ or $N(E) = 10^q x^m$. The values of m and q are given by

$$
\begin{aligned}
\gamma: \quad & m = 1.117 \pm 0.011; \;\; q = -11.02 \pm 0.19 \\
e^+: \quad & m = 1.129 \pm 0.011; \;\; q = -12.36 \pm 0.18 \\
e^-: \quad & m = 1.129 \pm 0.012; \;\; q = -12.17 \pm 0.20 \\
\mu^+: \quad & m = 0.922 \pm 0.006; \;\; q = -10.12 \pm 0.10 \\
\mu^- \quad & m = 0.923 \pm 0.006; \;\; q = -10.15 \pm 0.09
\end{aligned}
\tag{1}
$$

where m is the slope. m appears to be almost universal for all the components, while the intercept (q) depends on the component. The photon component is clearly dominant, followed by the electron, positron and the two muon components which appear to be superimposed. It would be interesting to see whether missing energy effects, due, for instance, to an increased multiplicity rate toward the production of weakly interacting particles can modify this type of inclusive measurements, thereby predicting variations in the slopes of the multiplicities respect to the Monte Carlo predictions reported here. One could entertain the possibility that a failure to reproduce this linear behaviour could be a serious problem for the theory and a possible signal of new physics. Given the large sets of simulations that we have performed, the statistical errors on the Monte Carlo results are quite small, and the Monte Carlo prediction appear to be rather robust. The difficulty of these measurements however, lay mainly in the energy reconstruction of the primary, with the possibility of a systematic error. However, once the reconstruction of the energy of the primary is under control among the various UHECR detectors, with a global calibration, these measurements could be a possible test for new physics. At the moment, however, we still do not have a quantification of the deviation from this behaviour such as that induced by supersymmetry or other competing theoretical models.

5.1 Directionality of the Bulk of the Shower

Another geometrical feature of the shower is the position of its bulk (measured as the opening of the radial cone at the radial distance where the maximum is achieved) as a function of the energy. This feature is illustrated in Fig. 6. Here we have plotted the averaged location of the multiplicity distribution as a function of the energy of the incoming primary. The geometrical center of the distributions tend to move slightly toward the vertical axis (higher collimation) as the energy increases. From the same plot it appears that the distributions of electrons, positrons and photons are closer to the center of the detector compared to the muon-antimuon distributions. As shown in the figure, the statistical errors on these results appear to be rather small.

5.2 The Overall Geometry of the Shower

As the shower develops in the atmosphere, we can monitor both the multiplicities of the various components and the average location of the bulk of the distributions at various observation levels. As we have mentioned above, we choose up to 9 observation levels spaces at about 13 km from one another. The lowest observation level is, according to our conventions, taken to coincide with the plane of the detector.

We show in Fig. 7a a complete simulation of the shower using a set of 9 observation levels, as explained above, at an energy of 10^{19} eV. In the simulation we assume that a first impact occurs near the top of the atmosphere at an eight of 113 km and we have kept this first impact fixed. The multiplicities show for all the components a rather fast growth within the first 10 km of crossing of the atmosphere after the impact, with the photon components growing faster compared to the others. The electron component also grows rather fast, and a similar behaviour is noticed for the muon/antimuon components, which show a linear growth in a logarithmic scale (power growth). In the following 40 km downward, from a height of 100 km down to 60 km, all the components largely conserve their multiplicities. Processes of regeneration of the various components and their absorption seem to balance. For the next 20 km, from a height of 60 km down to 40 km, all the components starts to grow, with the photon component showing a faster (power growth) with the traversed altitude. Slightly below 40 km of altitude the multiplicities of three components seem to merge (muons and electrons), while the photon component is still dominant by a factor of 10 compared to the others. The final development of the airshower is characterized by a drastic growth of all the components, with a final reduced muon component, a larger electron component and a dominant photon component. The growth in this last region (20 km wide) and in the first 20 km after the impact of the primary -in the upper part of the atmosphere- appear to be comparable. The fluctuations in the multiplicities of the components are rather small at all levels, as shown (for the photon case) in Fig.7b.

As we reach the GZK cutoff, increasing the energy of the primary by a factor of 10, the pattern just discussed in Fig. 7a is reproposed in Fig. 8a, though -in this case- the growth of the multiplicities of the subcomponents in the first 20 km from the impact and in the last 20 km is much stronger. The electron and the muon components appear to be widely separated, while the electron and positron components tend to be more overlapped. To the region of the first impact -and subsequent growth- follows an intermediate region, exactly as in the previous plots, where the two phenomena of production and absorption approximately balance one another and the multiplicities undergo minor variations. The final growth of all the components is, a this energy, slightly anticipated compared to Fig. 7a, and starts to take place at a height of 40 km and above and continues steadily until the first observation level. The photon remains the dominant component, followed by the electron and the muon component. Also in this case the fluctuations (pictured for the photon component only, Fig. 8b)

are rather small.

5.3 The Opening of the Shower

In our numerical study the geometrical center of each component of the shower is identified through a simple average with respect to all the distances from the core

$$R_M \equiv= \frac{1}{N} \sum_i R_i \tag{2}$$

where N is the total multiplicity at each selected observation level, R_i is the position of the produced particle along the shower and i runs over the single events. This analysis has been carried out for 9 equally spaced levels and the result of this study are shown in Figs. 9,10 and 8 at two different values of energy (10^{19} and 10^{20} eV). The opening of the various components are clearly identified by these plots. We start from Fig. 9. We have taken in this figure an original point of impact at a height of 113 Km, as in the previous simulations. It is evident that the photon component of the shower tends to spread rather far and within the first 20 km of depth into the atmosphere has already reached an extension of about 2 km; reaching a lateral extension of 10 km within the first 60 km of crossing of the atmosphere.

Starting from a height of 50 km down to 10 km, the shower gets reabsorbed (turns toward the center) and is characterized by a final impact which lays rather close to the vertical axis. Electrons and photons follow a similar behaviour, except that for electrons whose lateral distribution in the first section of the development of the shower is more reduced. The muonic (antimuons) subcomponents appear to have a rather small opening and develop mostly along the vertical axis of impact. In the last section of the shower all the components get aligned near the vertical axis and hit the detector within 1 km.

Few words should be said about the fluctuations. At 10^{19} eV, as shown in Fig. 9b, the fluctuations are rather large, especially in the first part of the development of the shower. These turn out to be more pronounced for photons, whose multiplicity growth is large and very broad. As we increase the energy of the primary to 10^{20} eV the fluctuations in the lateral distributions (see Fig. 10b) are overall reduced, while the lateral distributions of the photons appear to be drastically reduced (Fig. 10a).

6 Can we detect new physics at Auger?

There are various issues that can be addressed, both at theoretical and at experimental level, on this point, one of them being an eventual confirmation of the real existence of events above the cutoff. However, even if these measurement will confirm their existence, it remains yet to be seen whether any additional new physics can be inferred just from an analysis of the air shower. A possibility might be supersymmetry or any new underlying interaction, given the large energy available in

the first impact. We recall that the spectrum of the decaying X-particle (whatever its origin may be), prior to the atmospheric impact of the UHECR is of secondary relevance, since the impact is always due to a single proton. Unless correlations are found among different events - and by this we mean that a large number of events should be initiated by special types of primaries - we tend to believe that effects due to new interactions are likely to play a minor role.

In previous works we have analyzed in great detail the effects of supersymmetry in the formation of the hadronic showers. These studies, from our previous experience [21, 22, 23], appear to be rather complex since they involve several possible intermediate and large final scales and cannot possibly be conclusive. There are some obvious doubts that can be raised over these analysis, especially when the DGLAP equations come to be extrapolated to such large evolution scales, even with a partial resummation of the small-x logarithms. In many cases results obtained in this area of research by extrapolating results from collider phenomenology to extremely high energies should be taken with extreme caution in order to reduce the chances of inappropriate hasty conclusions. What is generally true in a first approximation is that supersymmetric effects do appear to be mild [21, 22, 23]. Rearrangements in the fragmentation spectra or supersymmetric effects in initial state scaling violations are down at the few percent level. We should mention that the generation of supersymmetric scaling violations in parton distributions, here considered to be the bulk of the supersymmetric contributions, are rather mild if the entrance into the SUSY region takes place "radiatively" as first proposed in [21, 22]. This last picture might change in favour of a more substantial signal if threshold enhancements are also included in the evolution, however this and other related points have not yet been analyzed in the current literature.

6.1 The Primary Impact and a Simple Test

Our objective, at this point, is to describe the structural properties of the shower with an emphasis on the dynamics of the first impact of the primary with the atmosphere, and at this stage one may decide to look for the emergence of possible new interactions, the most popular one being supersymmetry.

One important point to keep into consideration is that the new physical signal carried by the primaries in these collisions is strongly "diluted" by their interaction with the atmosphere and that large statistical fluctuations are immediately generated both by the randomness of the first impact, the variability in the zenith angle of the impact, and the -extremely large- phase space available at those energies in terms of fragmentation channels. We can't possibly underestimate these aspects of the dynamics, which are at variance with previous analysis, where the search for supersymmetric effects (in the vacuum) seemed to ignore the fact that our detectors are on the ground and not in space.

For this reason we have resorted to a simple and realistic analysis of the structure

of airshowers as can be obtained from the current Monte Carlo.

The simplest way to test whether a new interaction at the first proton-proton impact can have any effect on the shower is to modify the cross section at the first atmospheric impact using CORSIKA in combination with some of the current hadronization models which are supposed to work at and around the GZK cutoff. There are obvious limitations in this approach, since none of the existing codes incorporates any new physics beyond the standard model, but this is possibly one of the simplest ways to proceed. For this purpose we have used SYBILL [24], with the appropriate modifications discussed below.

To begin let's start by recalling one feature of the behaviour of the hadronic cross section ($p\,p$ or $p\,\bar{p}$) at asymptotically large energies. There is evidence (see [25]) demonstrating a saturation of the Froissart bound of the total cross section with rising total energy, s. This $\log^2(s)$ growth of the total cross section is usually embodied into many of the hadronization models used in the analysis of first impact and leaves, therefore, little room for other substantial growth with the opening of new channels, supersymmetry being one of them. We should also mention that various significant elaborations [26] on the growth of the total cross section and the soft pomeron dominance have been discussed in the last few years and the relation of this matter [27] with the UHECR events is of utmost relevance.

With this input in mind we can safely "correct" the total cross section by at most a (nominal) factor of 2 and study whether these nominal changes can have any impact on the structural properties of the showers.

We run simulations on the showers generated by this modification and try to see whether there is any signal in the multiplicities which points toward a structural (multiplicity, geometrical) modification of the airshowers in all or some of its subcomponents. For this purpose we have performed runs at two different energies, at the GZK cutoff and 1 decade below, and analyzed the effects due to these changes.

We show in two figures results on the multiplicities, obtained at zero zenith angle, of some selected particles (electrons and positrons, in our case, but similar results hold for all the dominant components of the final shower) obtained from a large scale simulation of air showers at and around the GZK cutoff. We have used the simulation code CORSIKA for this purpose.

In Figs. 11-15 we show plots obtained simulating an artificial first proton impact in which we have modified the first interaction cross section by a nominal factor ranging from 0.7 to 2. We plot on the y-axis the corresponding fluctuations in the multiplicities both for electrons and positrons. Statistical fluctuations [§] have been estimated using bins of 80 runs. The so-developed showers have been thinned using the Hillas algorithm, as usually done in order to make the results of these simulations manageable, given the size of the showers at those energies. As one can immediately see, the artificial corrections on the cross section are compatible with ordinary fluc-

[§]we keep the height of the first proton impact with the atmosphere arbitrary for each selected correction factor (x-axis)

tuations of the air-shower. We have analyzed all the major subcomponents of the air shower, photons and leptons, together with the corresponding neutrino components. We can summarize these findings by assessing that a modified first impact, at least for such correction factors in the 0.7-2 range in the cross section, are unlikely to modify the multiplicities in any appreciable way.

A second test is illustrated in Figs. 16-20. Here we plot the same correction factors on the x-axis as in the previous plots (11-15) but we show on the y-axis (for the same particles) the average point of impact on the detector and its corresponding statistical fluctuations. As we increase the correction factor statistical fluctuations in the formation of the air shower seem to be compatible with the modifications induced by the "new physics" of the first impact and no special new effect is observed.

Fluctuations of these type, generated by a minimal modification of the existing codes only at the first impact may look simplistic, and can possibly be equivalent to ordinary simulations with a simple rescaling of the atmospheric height at which the first collision occurs, since the remaining interactions are, in our approach, unmodified. The effects we have been looking for, therefore, appear subleading compared to other standard fluctuations which take place in the formation of the cascade. On the other hand, drastic changes in the structure of the air shower should possibly depend mostly on the physics of the first impact and only in a less relevant way on the modifications affecting the cascade that follows up. We have chosen to work at an energy of 10^{20} eV but we do not observe any substantial modifications of our results at lower energies (10^{19} eV), except for the multiplicities which are down by a factor of 10. Our brief analysis, though simple, has the purpose to illustrate one of the many issues which we believe should be analyzed with great care in the near future: the physics of the first impact and substantial additional modifications to the existing codes in order to see whether any new physics can be extracted from these measurements.

7 Conclusions

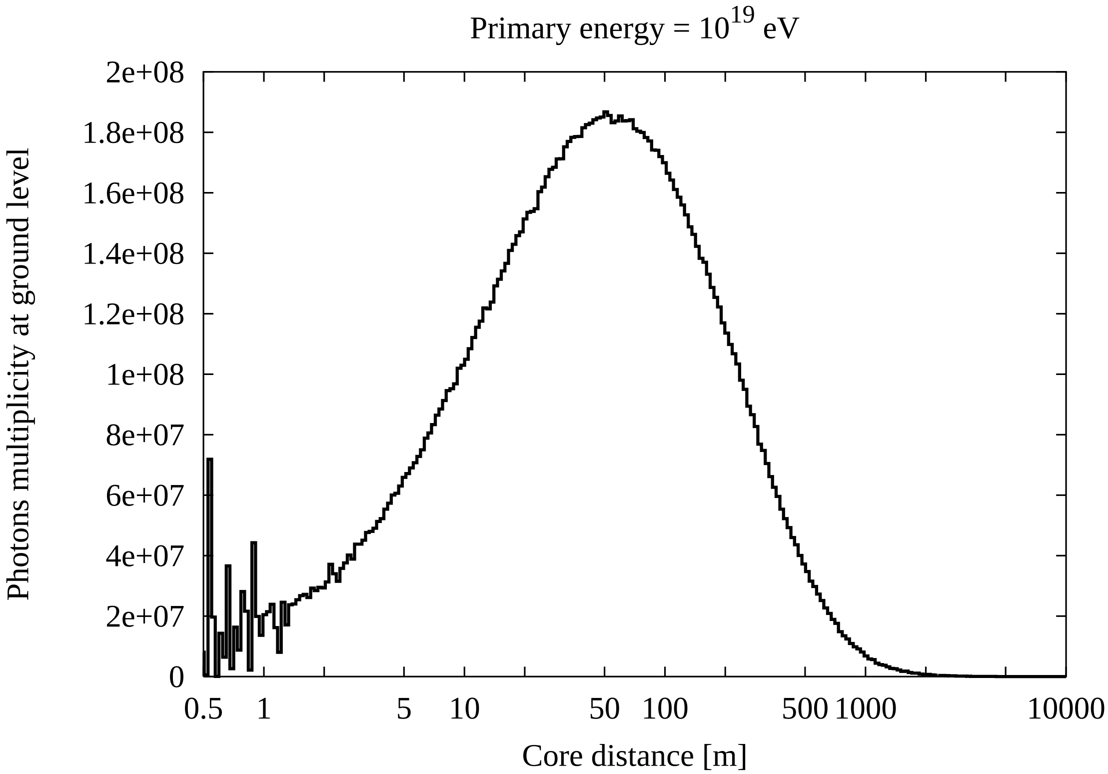
We have tried to analyze with a searching criticism the possibility of detecting new physics at AUGER using current ideas about supersymmetry, the QCD evolution and such. While the physics possibilities of these experiments are far reaching and may point toward a validation or refusal of the existence of a GZK cutoff, we have argued that considerable progress still needs to be done in order to understand better the hadronization models at very large energy scales. Our rather conservative viewpoint stems from the fact that the knowledge of the structure of the hadronic showers at large energies is still under debate and cannot be conclusive. We have illustrated by an extended and updated simulation some of the characteristics of the showers, the intrinsic fluctuations in the lateral distributions, the multiplicities of the various subcomponents and of the total spectrum, under some realistic conditions. We have

also tried to see whether nominal and realistic changes in the cross section of the first impact may affect the multiplicities, with a negative outcome. We have however pointed out, in a positive way, that new physics models predicting large missing energy may have a chance to be identified, since the trend followed by the total multiplicities (in a log-log scale) appear to be strikingly linear.

We do believe, however, that other and even more extensive simulation studies should be done, in combination with our improved understanding of small-x effects in QCD at large parton densities, in order to further enhance the physics capabilities of these experiments. Another improvement in the extraction of new physics signals from the UHECR experiments will come from the incorporation of new physics in the hadronization models.

Acknowledgments

We thank D. Martello and Philippe Jetzer for discussions and Prof. D. Heck for correspondence. The work of A.C. and C.C. is supported in part by INFN (iniziativa specifica BA-21). The work of A.F. is supported in part by PPARC. Simulations have been performed using the INFN-LECCE/Astrophysics computational cluster. C.C. thanks the University of Oxford and the Theory Group at the University. of Zurich (Irchel) for hospitality while completing this work.



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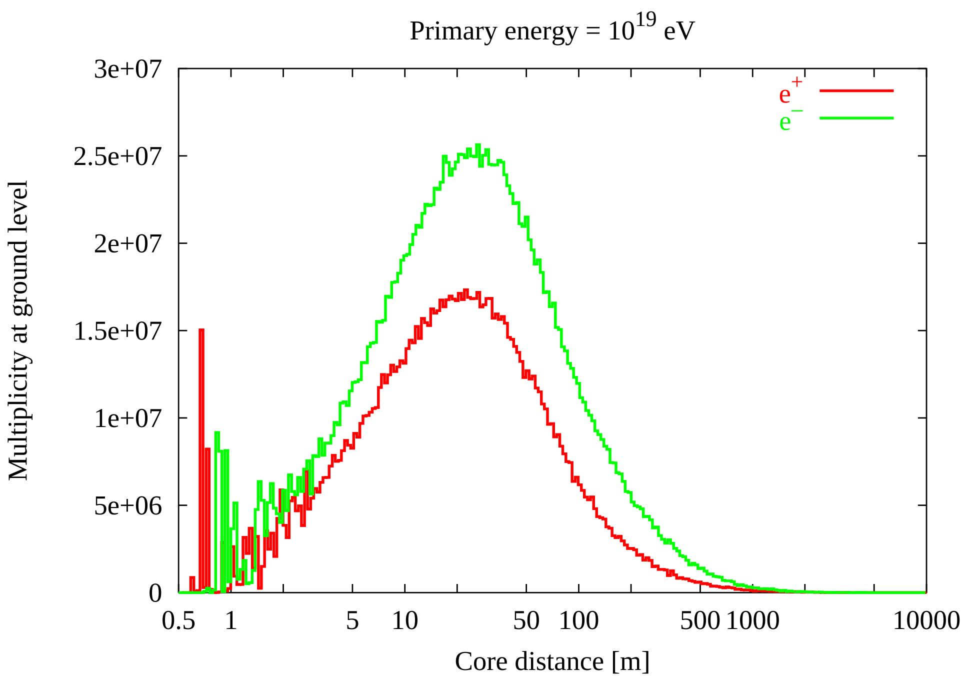
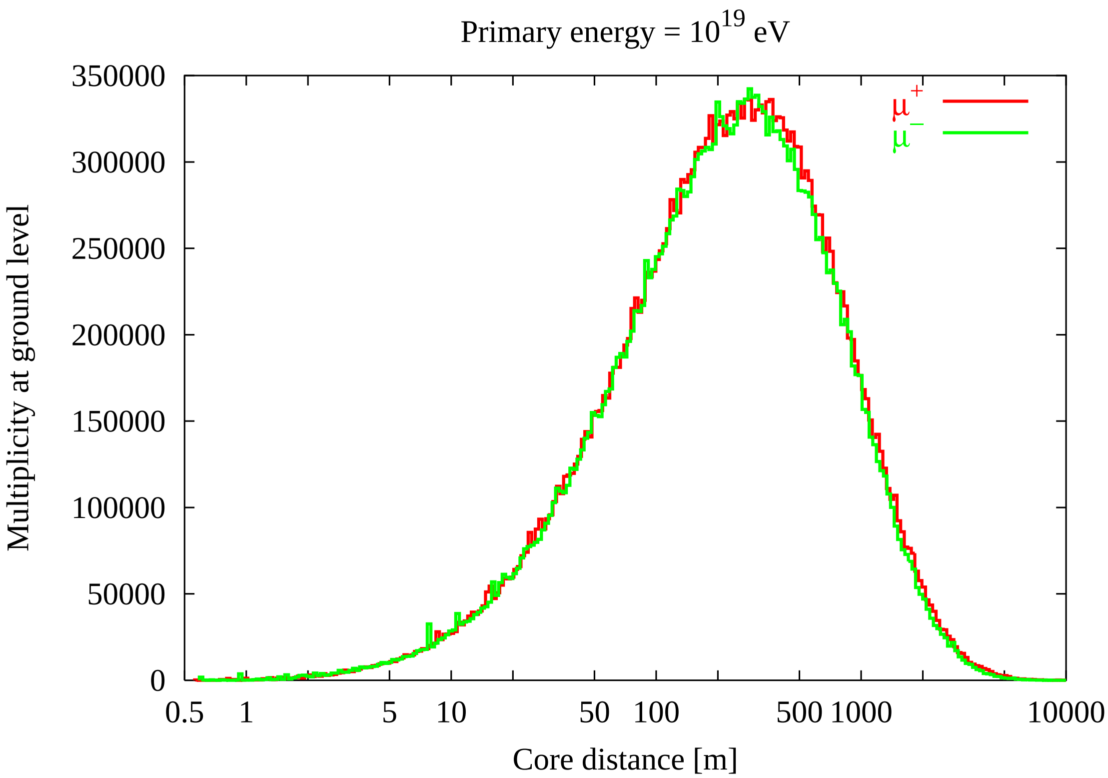


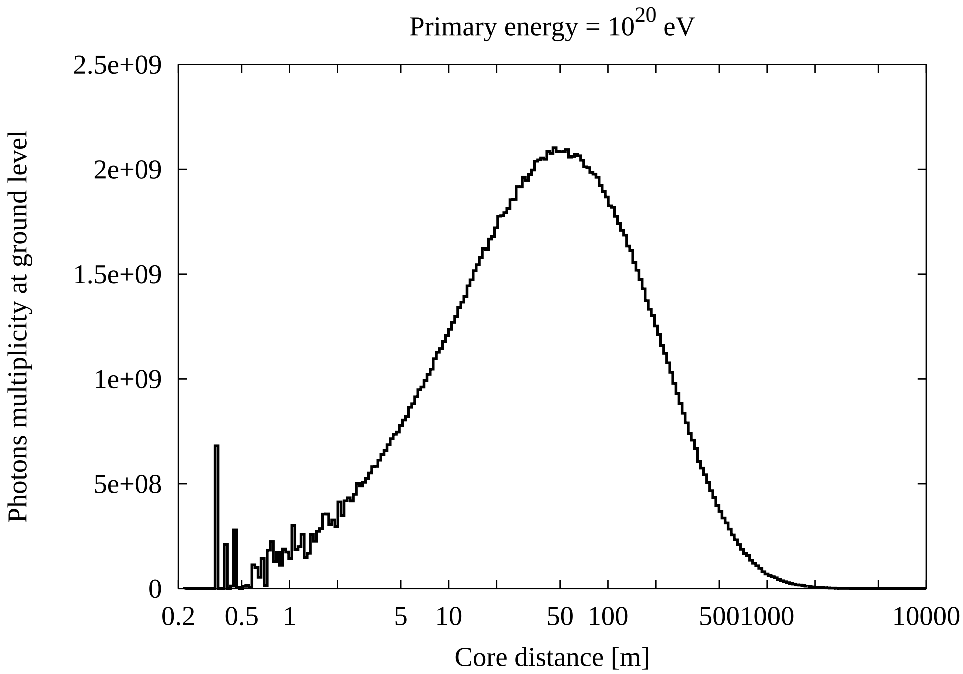
(b)

Figure 1: Multiplicities of photons and $e^{\pm}$ at the ground level with a proton primary of 10^{19} eV as a function of the distance from the core of the shower.



(a)

Figure 2: Multiplicities of $\mu^{\pm}$ at the ground level with a proton primary of 10^{19} eV as a function of the distance from the core of the shower.



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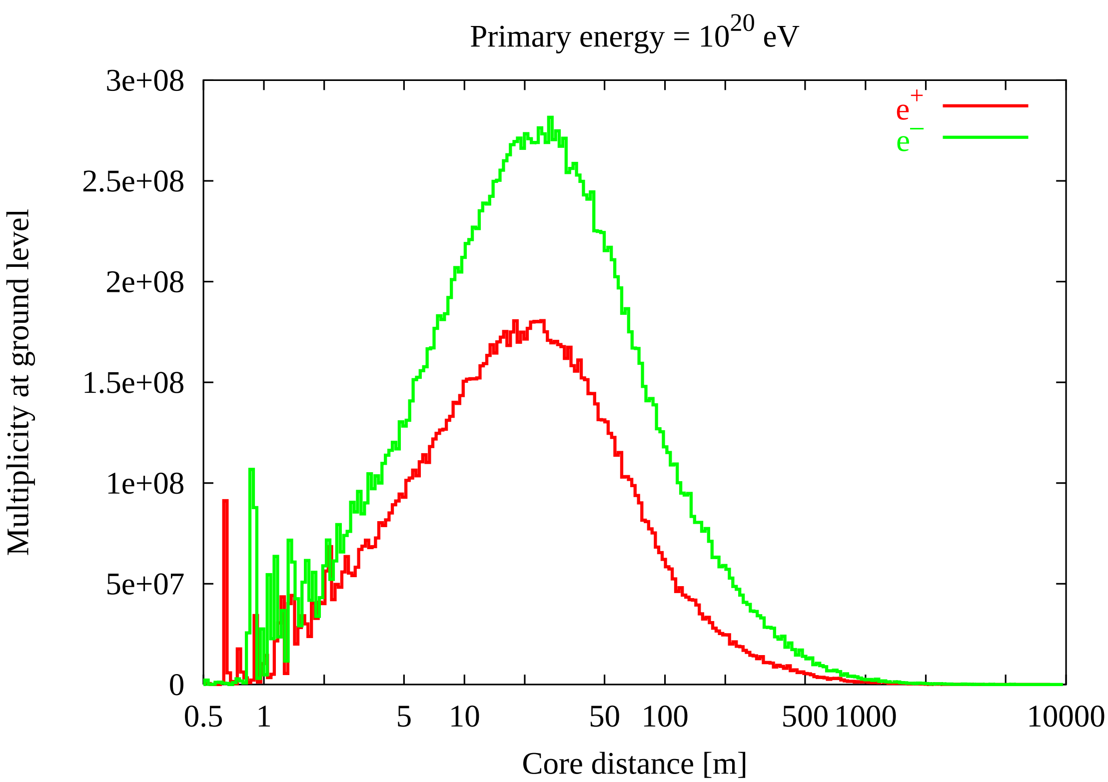

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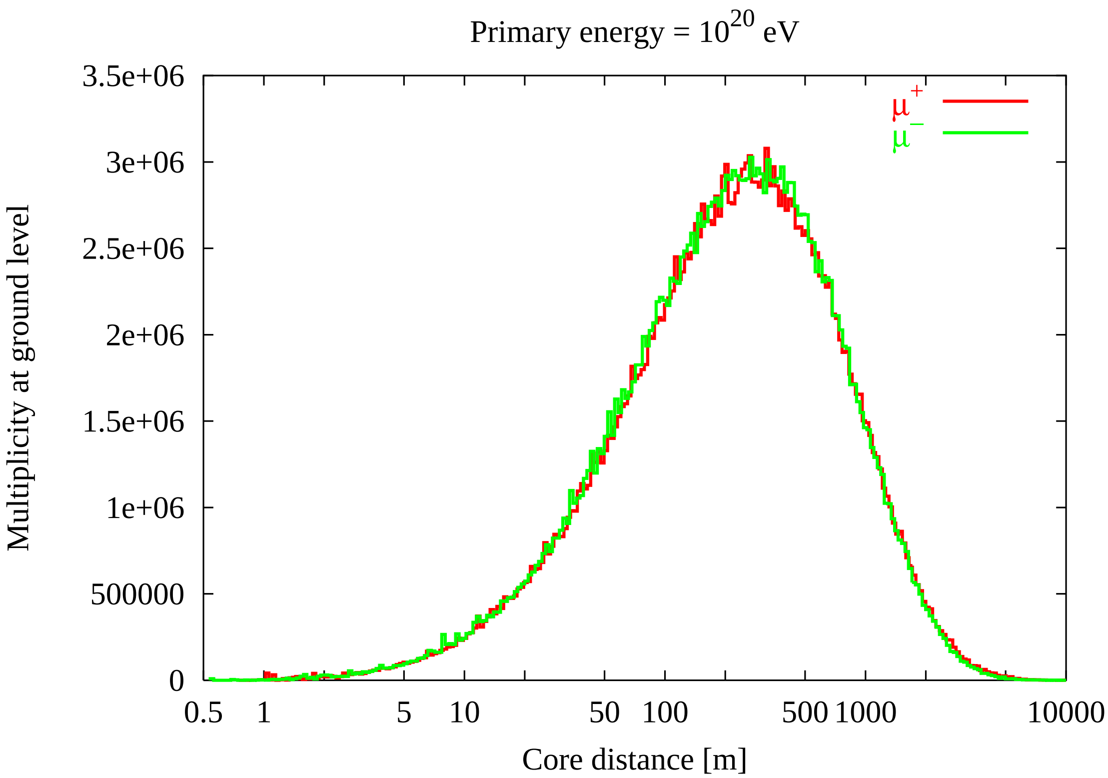
Figure 3: Multiplicities of photons and $e^{\pm}$ at the ground level with a proton primary of 10^{20} eV as a function of the distance from the core of the shower.



(a)

Figure 4: Multiplicities of $\mu^{\pm}$ at the ground level with a proton primary of 10^{20} eV as a function of the distance from the core of the shower.

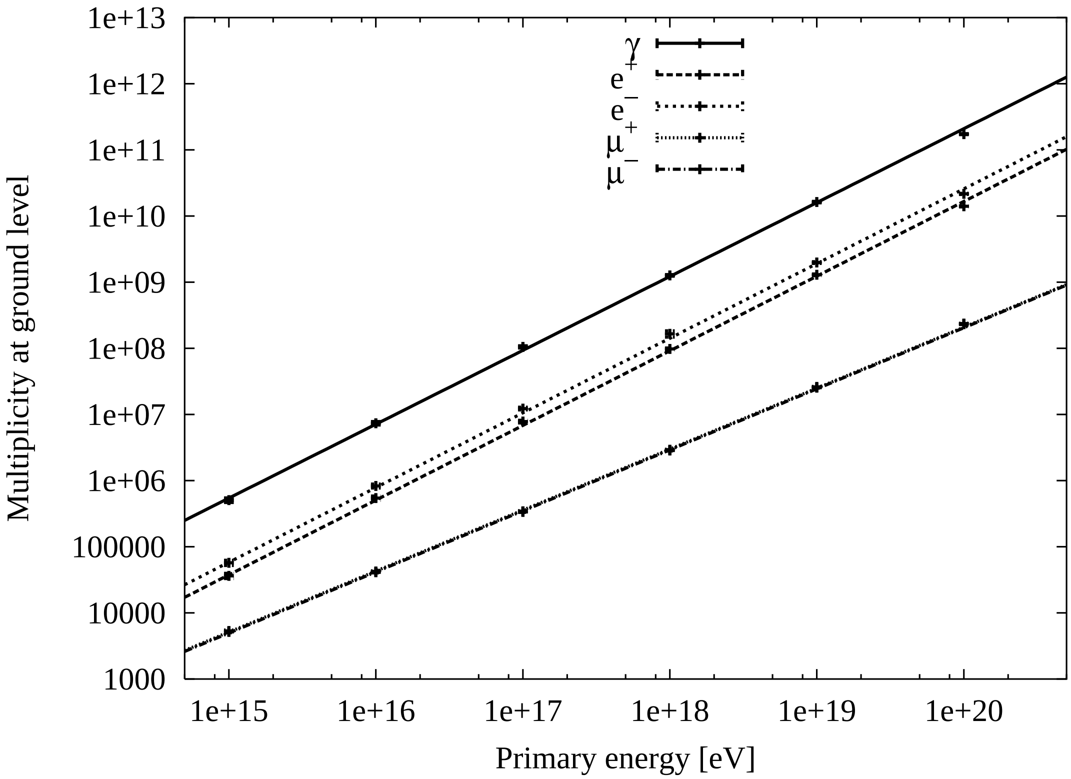


Figure 5: Multiplicities of photons, $e^{\pm}$, $\mu^{\pm}$ at the ground level as a function of the primary energy. Due to the logarithmic scale, μ^{+} and μ^{-} look superimposed.

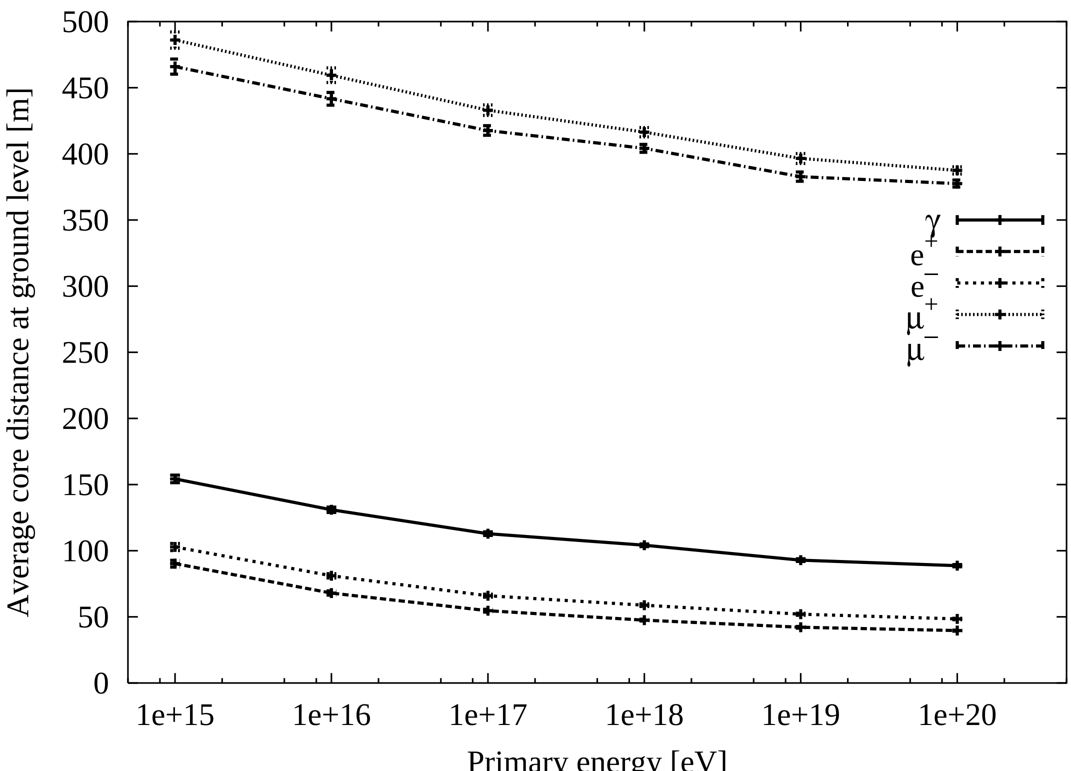
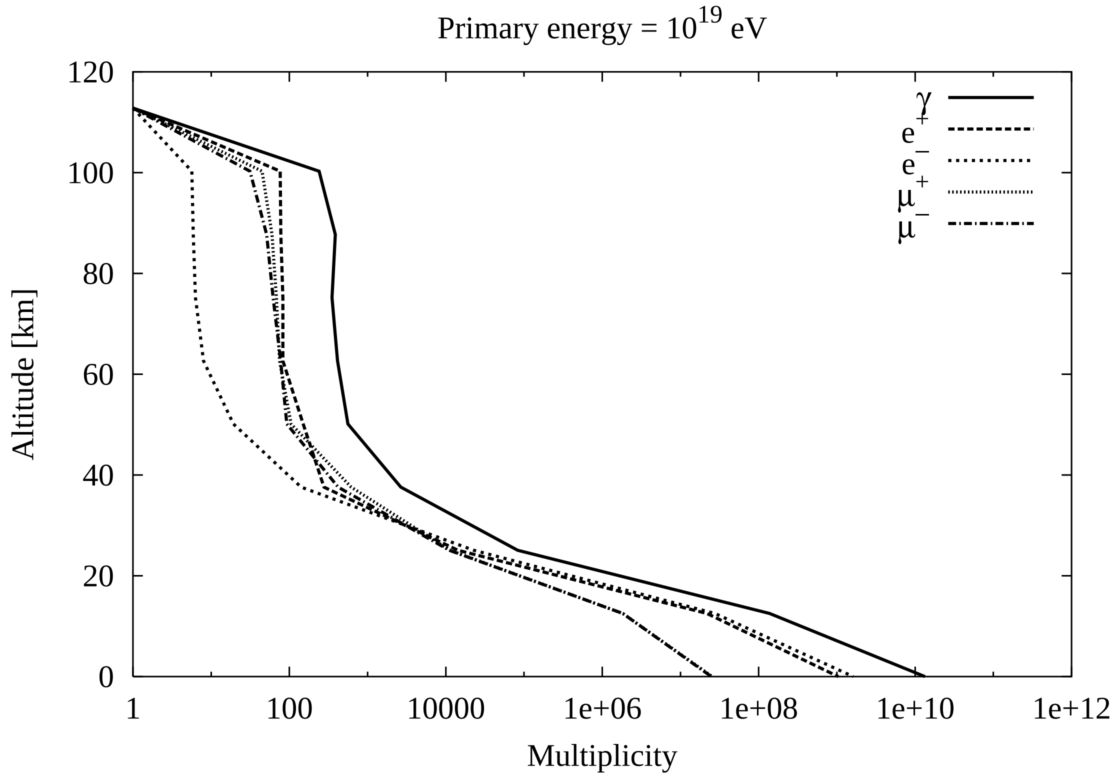


Figure 6: Average distance from the core of the shower of photons, $e^{\pm}$, $\mu^{\pm}$ at the ground level as a function of the primary energy.



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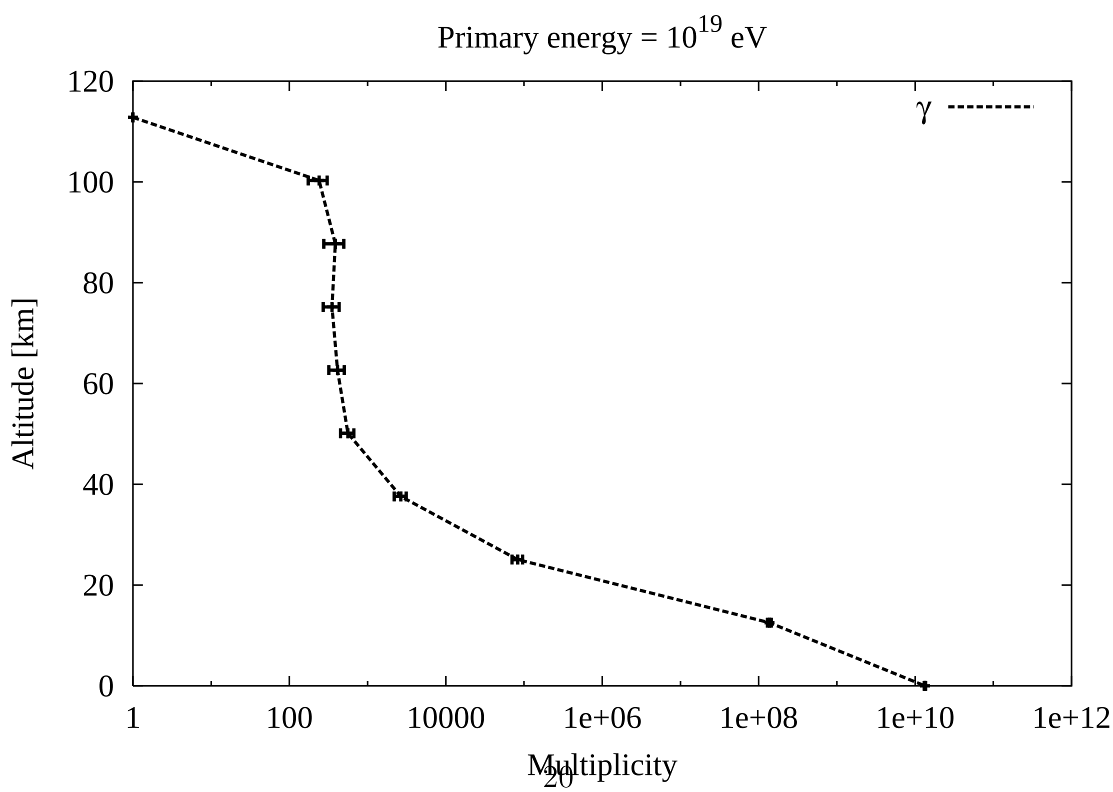
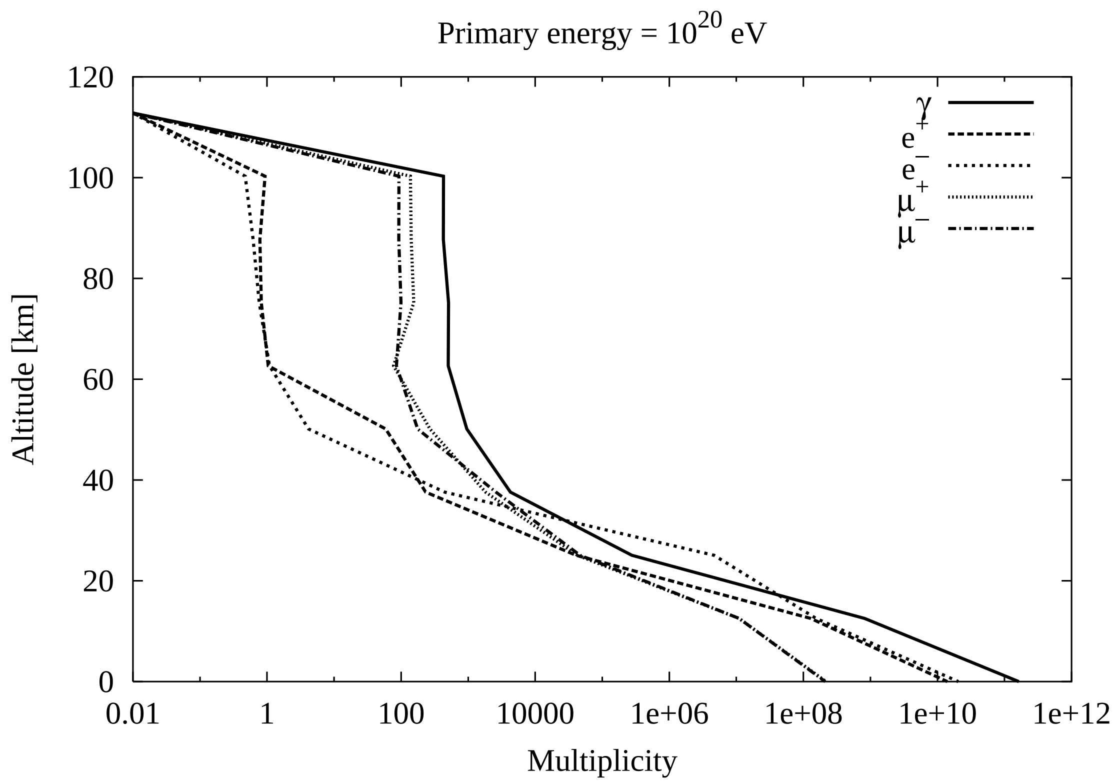


(b)

Figure 7: Multiplicities of photons, $e^{\pm}$, $\mu^{\pm}$ at various levels of observations for a primary energy of 10^{19} eV. The first impact is forced to occur at the top of the atmosphere. In the subfigure (b) we show the uncertainties just in the case of the



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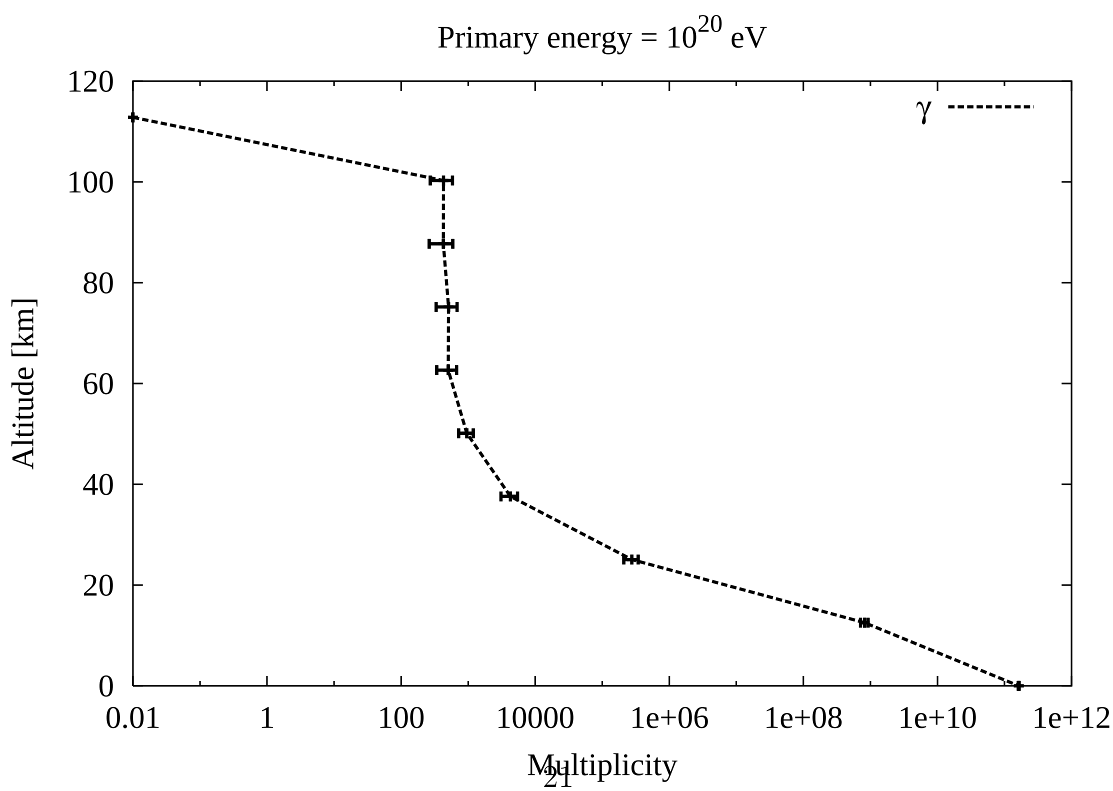
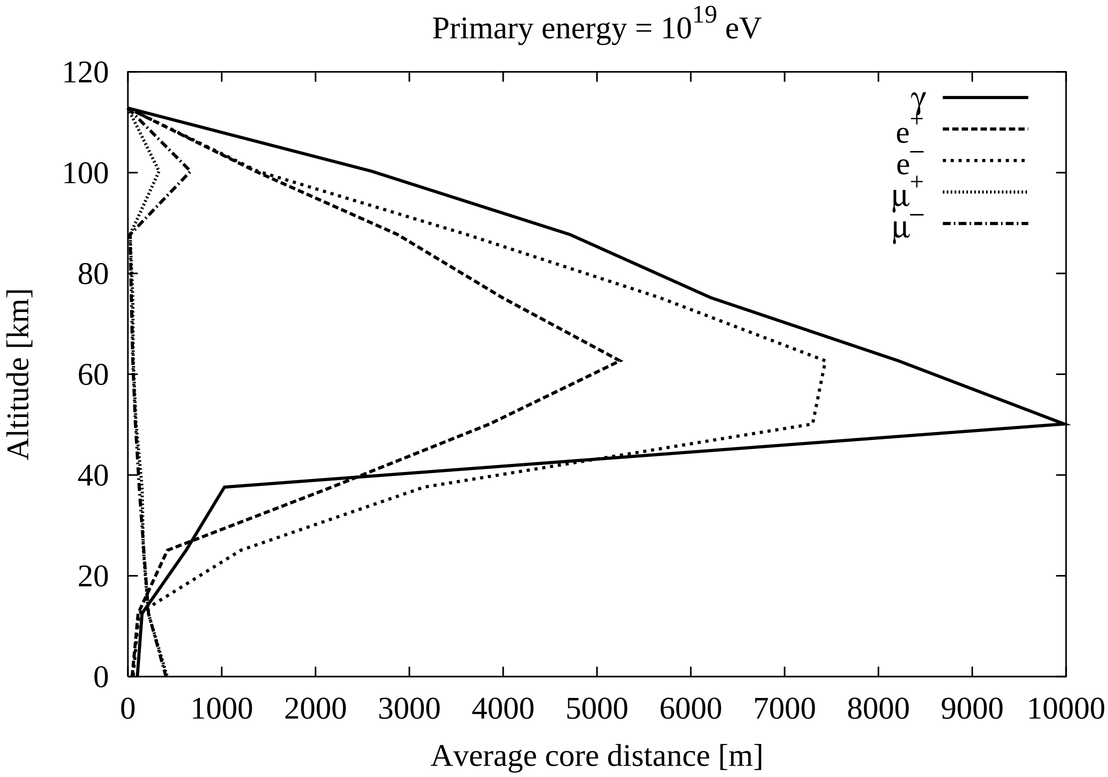


(b)

Figure 8: Multiplicities of photons, $e^{\pm}$, $\mu^{\pm}$ at various levels of observations for a primary energy of 10^{20} eV. The first impact is forced to occur at the top of the atmosphere. In the subfigure (b) we show the uncertainties just in the case of the



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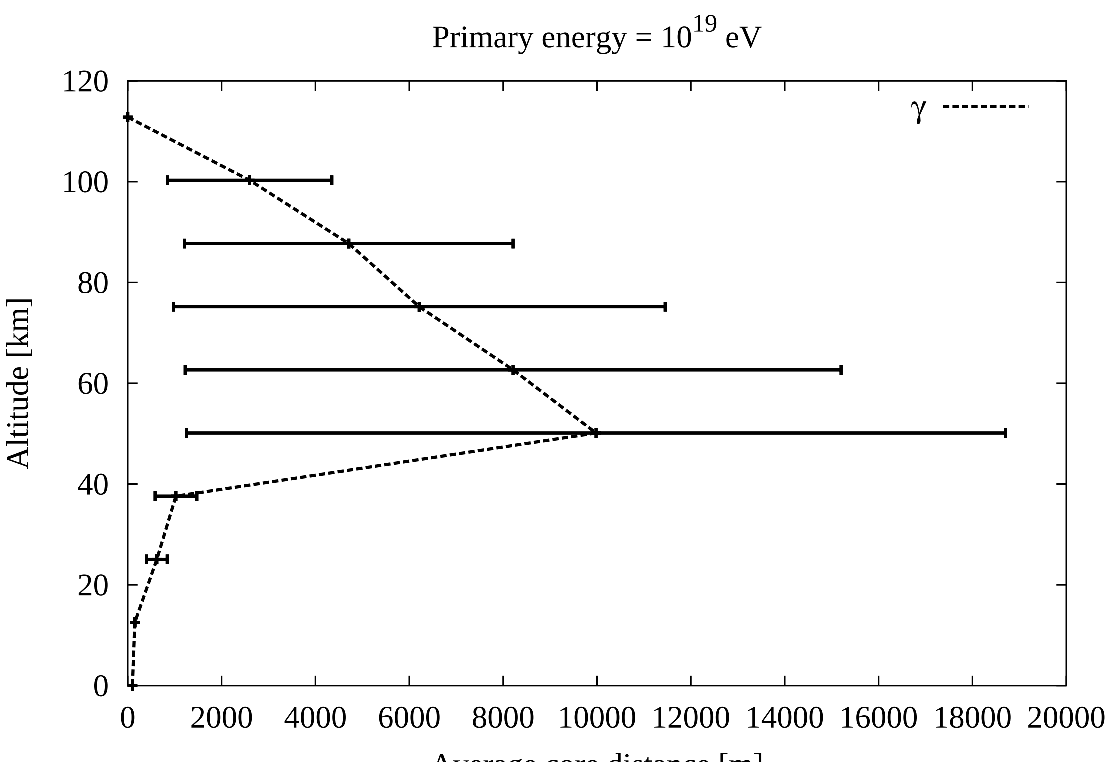
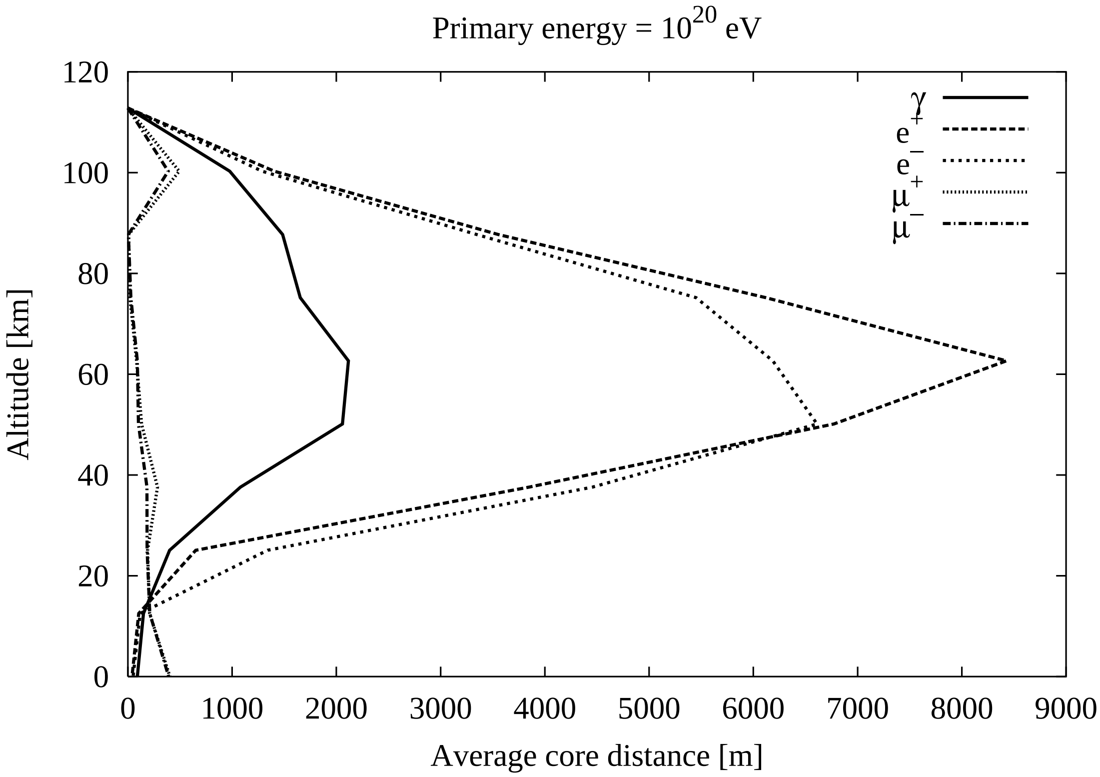


(b)

Figure 9: Average core distances of photons, $e^{\pm}$, $\mu^{\pm}$ at various levels of observations for a primary energy of 10^{19} eV. The first impact is forced to occur at the top of the atmosphere. In the subfigure (b) we show the uncertainties just in the case of the



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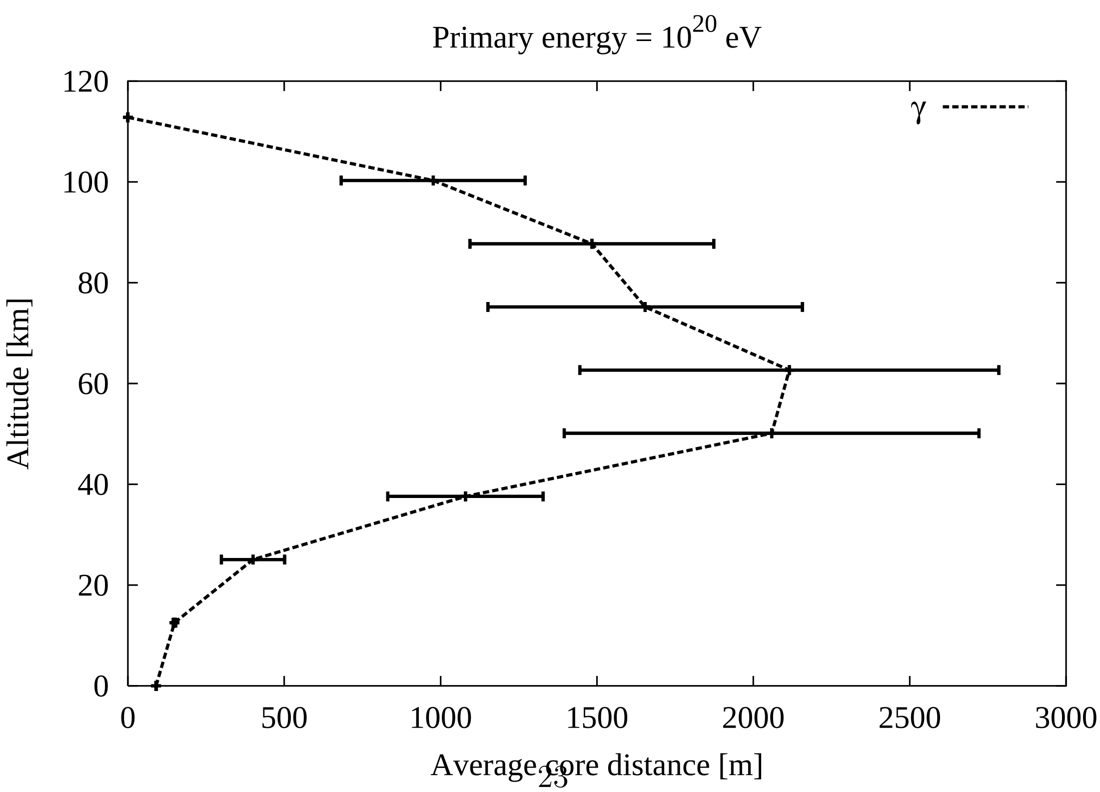

(b)

Figure 10: Average core distances of photons, $e^{\pm}$, $\mu^{\pm}$ at various levels of observations for a primary energy of 10^{20} eV. The first impact is forced to occur at the top of the atmosphere. In the subfigure (b) we show the uncertainties just in the case of the

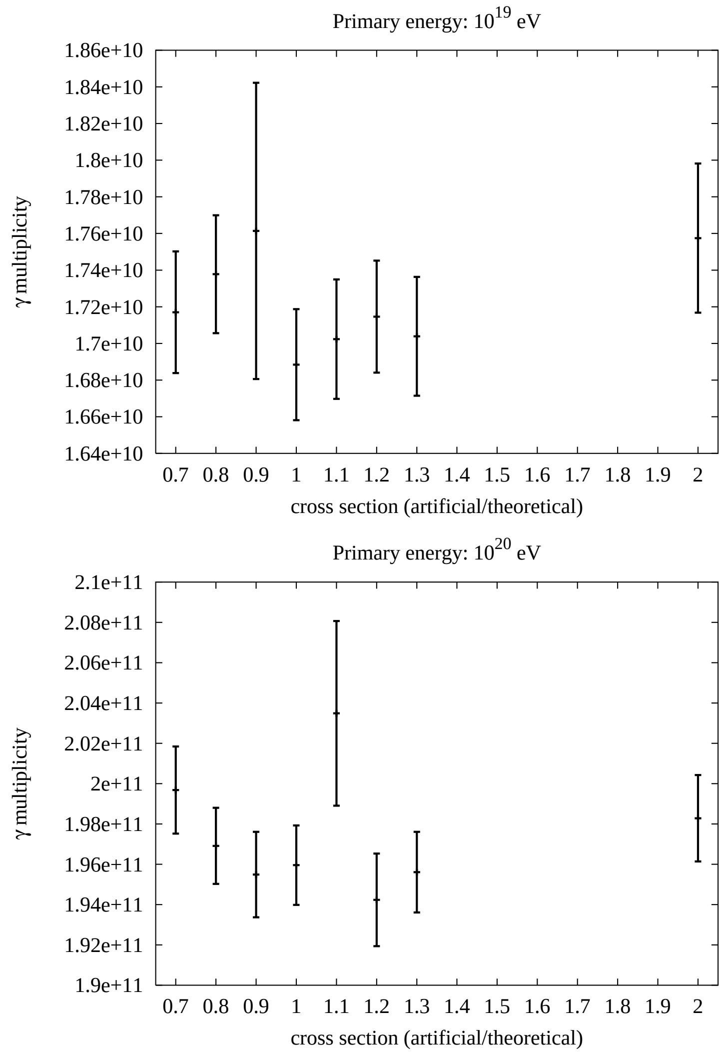

Figure 11: variation of the photon multiplicity as a function of the first impact cross section at 10^{19} and at 10^{20} eV

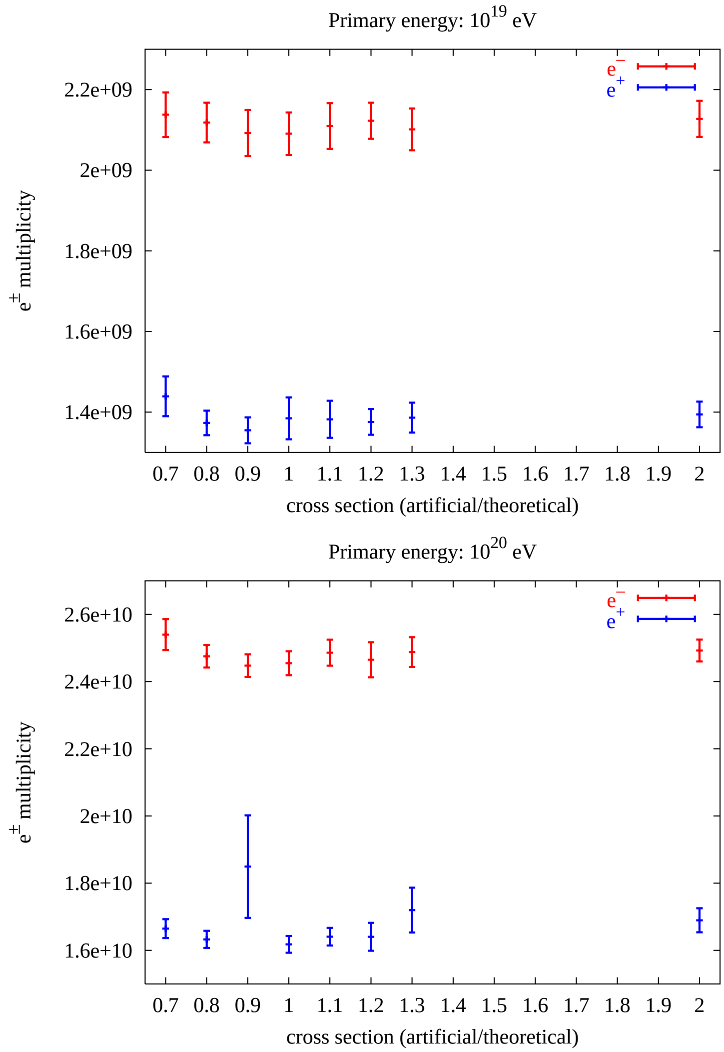

Figure 12: variation of the $e^{\pm}$ multiplicity as a function of the first impact cross section at 10^{19} and at 10^{20} eV

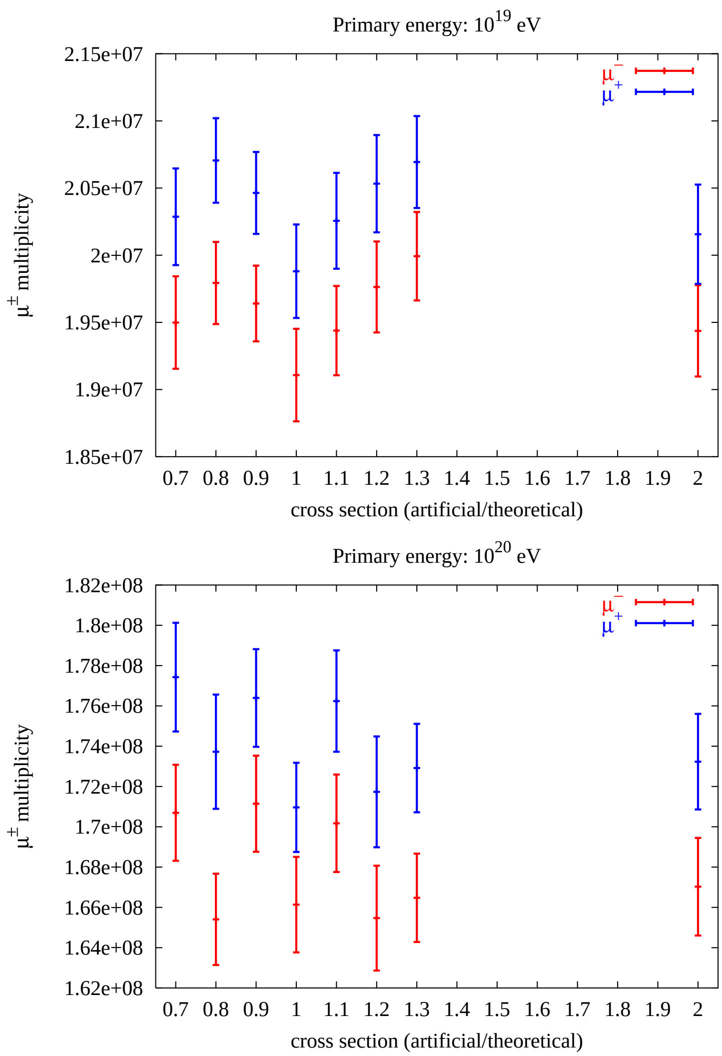

Figure 13: variation of the $\mu^{\pm}$ multiplicity as a function of the first impact cross section at 10^{19} and at 10^{20} eV

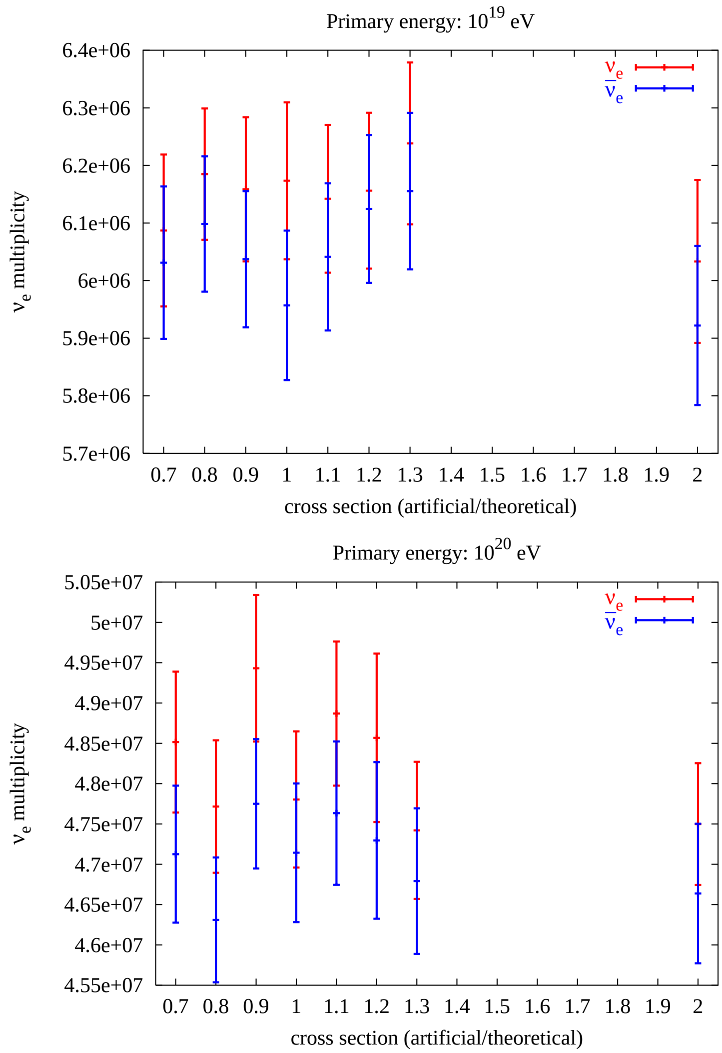

Figure 14: variation of the ν_e multiplicity as a function of the first impact cross section at 10^{19} and at 10^{20} eV

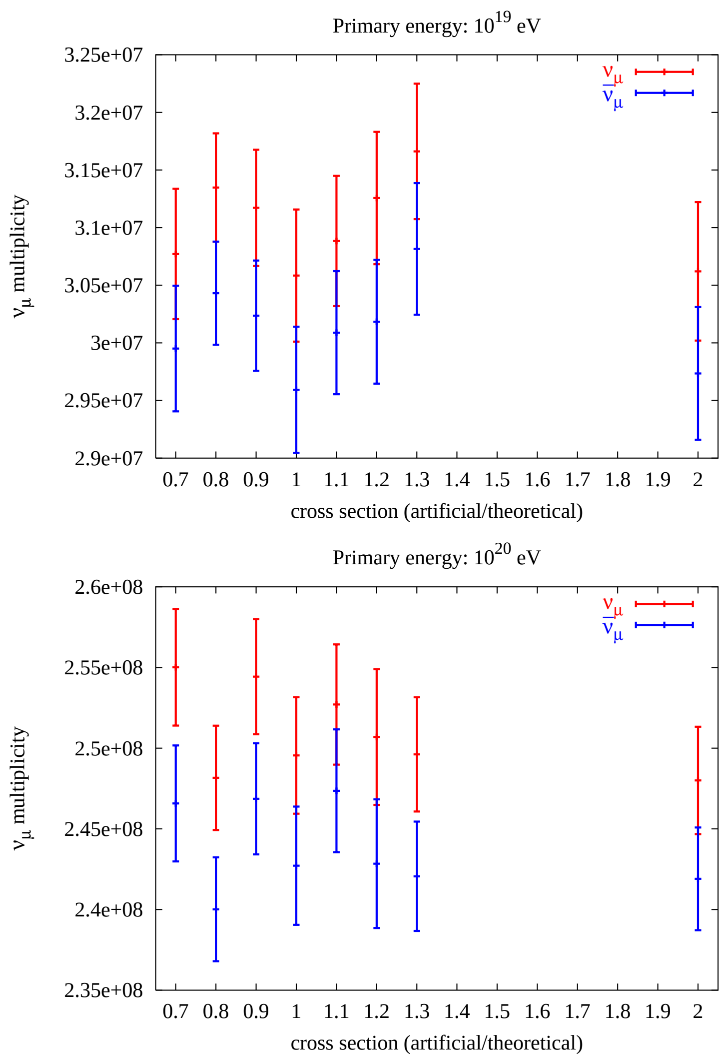

Figure 15: variation of the ν_μ multiplicity as a function of the first impact cross section at 10^{19} and at 10^{20} eV

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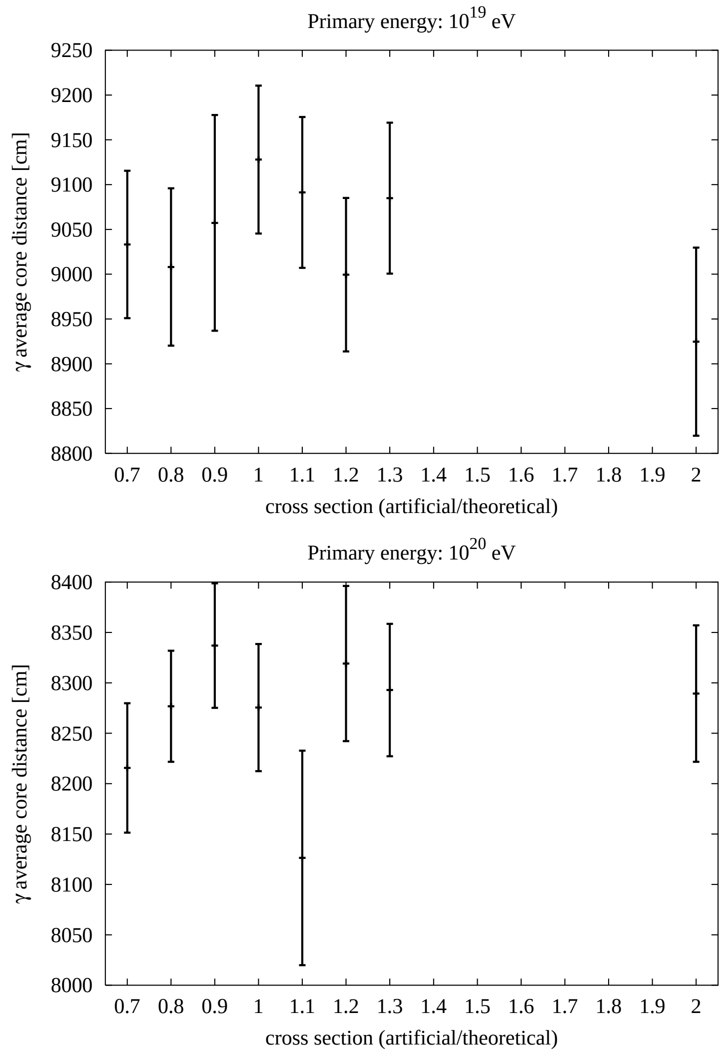


Figure 16: Lateral distributions of photons as a function of the first impact cross section at 10^{19} and at 10^{20} eV

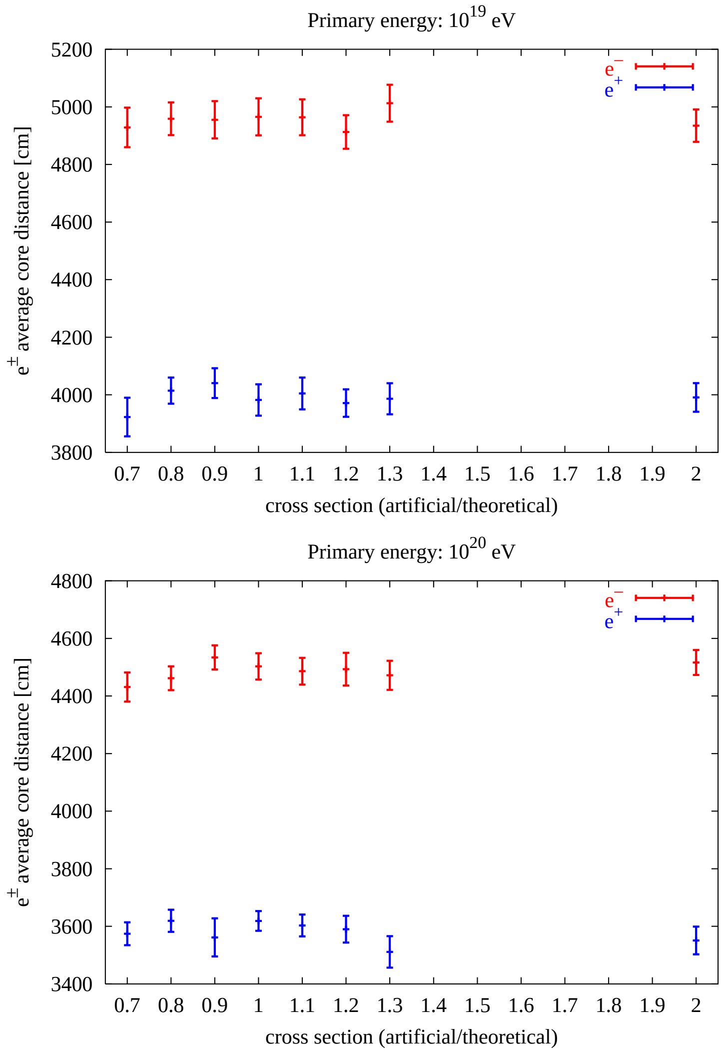
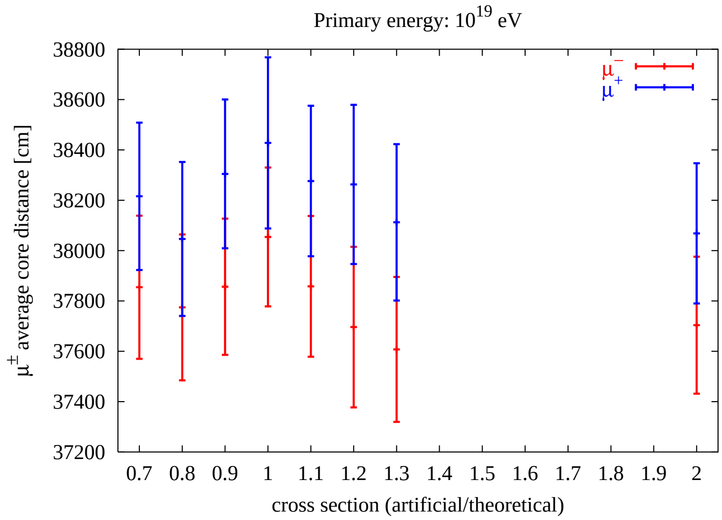


Figure 17: Lateral distributions of $e^{\pm}$ as a function of the first impact cross section at 10^{19} and at 10^{20} eV



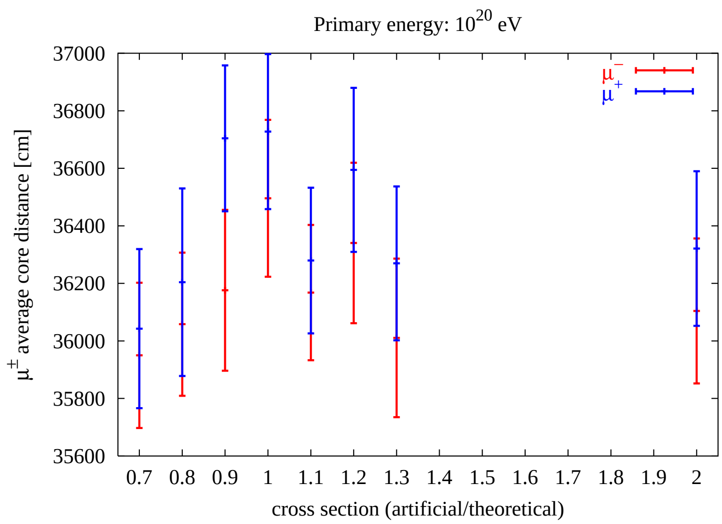


Figure 18: Lateral distributions of $\mu^{\pm}$ as a function of the first impact cross section at 10^{19} and at 10^{20} eV

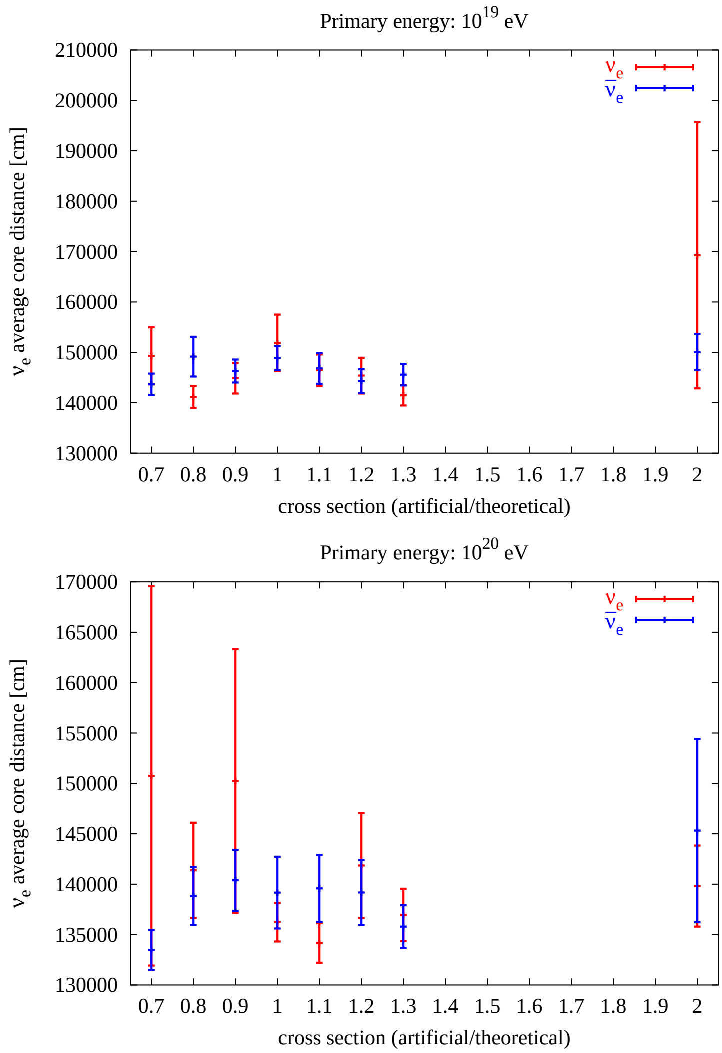


Figure 19: Lateral distributions of ν_e as a function of the first impact cross section at 10^{19} and at 10^{20} eV

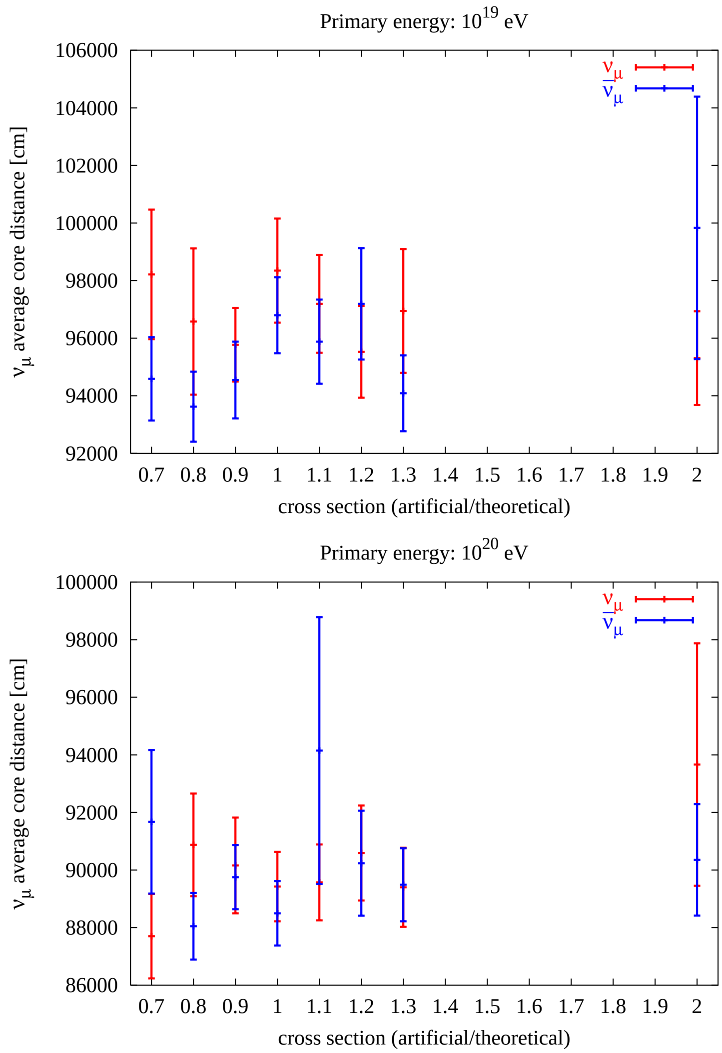


Figure 20: Lateral distributions of ν_μ as a function of the first impact cross section at 10^{19} and at 10^{20} eV